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Article

A Systematic Literature Review of Multi-Criteria Decision-Making Methods for Sustainable Selection of Insulation Materials in Buildings

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Abstract: The European Commission has recently adopted the Renovation Wave Strategy, aiming at the improvement of the energy performance of buildings. The strategy aims to at least double renovation rates in the next ten years and make sure that renovations lead to higher energy and resource efficiency. The choice of appropriate thermal insulation materials is one of the simplest and, at the same time, the most popular strategies that effectively reduce the energy demand of buildings. Today, the spectrum of insulation materials is quite wide, and each material has its own specific characteristics. It is recognized that the selection of materials is one of the most challenging and difficult steps of a building project. This paper aims to give an in-depth view of existing multi-criteria decision-making (MCDM) applications for the selection of insulation materials and to provide major insights in order to simplify the process of methods and criteria selection for future research. A systematic literature review is performed based on the Search, Appraisal, Synthesis and Analysis (SALSA) framework and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. In order to determine which MCDM method is the most appropriate for different questions, the main advantages and disadvantages of different methods are provided.

Keywords: thermal insulation; multi criteria analysis; MCDM; SALSA; buildings; Renovation Wave

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1. Introduction

The issue of sustainable energy development is one of the most important in various political documents. The construction sector, which consumes about 40% of the total primary energy [1,2] and emits 10% of CO_2 emissions [3], plays a significant role in addressing these issues. Renovation of buildings is a priority of the EU Renovation Wave Strategy adopted in 2020 [4]. The Renovation Wave Strategy aims to at least double renovation rates in the next ten years and ensure that energy renovations of buildings will provide higher energy efficiency and significant GHG emission reduction. Therefore, optimization of energy needs in buildings is an important aspect in the fight against climate change [5]. Most of the energy in buildings is used to meet the needs of heating, ventilation, and air conditioning [6]. Significant energy savings in buildings can be achieved by choosing appropriate building design solutions. Heat consumption is effectively reduced by improving the insulation properties of buildings; therefore, increasing the energy efficiency of buildings has become an important aspect of national energy strategies in many countries [7]. A lot of initiatives focus on the construction sector and there are many objectives aimed at promoting technological innovation, improving energy efficiency [8], reducing environmental impact [9], and improving life quality criteria [10]. Although extensive attention in the construction of new buildings has been paid to energy efficiency issues, new buildings account for only about 1% of the housing market annually [3]. Therefore, in order to reduce energy consumption, old buildings must be renovated with a strong focus on energy efficiency issues. In the European Union, the new Energy Performance of Buildings Directive (EPBD) 2018/844 highlights the issue of energy efficiency in buildings and sets out certain requirements and objectives to be pursued [11]. The aim is that both new and renovated buildings become zero-energy buildings, which have high energy efficiency, and in which renewable energy sources meet the greatest energy demand.

Building insulation materials play a particularly significant role in achieving the goals of energy efficiency in buildings. The choice of appropriate thermal insulation materials is one of the simplest and at the same time the most popular strategies that effectively reduce the energy demand of buildings [12,13]. The choice of insulation materials depends not only on the thermal efficiency of the building. The choice of materials can also determine the aspects related to the quality of life and the impact on the environment [14]. Today, the spectrum of insulation materials is quite wide, and each material has its own specific characteristics. Some materials are environmentally friendly, while others are more economically acceptable, and the rest have better thermal insulation properties [14–18]. The choice of materials in the case of a particular project and individual country depends on different factors, such as price, material availability factors, transportation costs, construction rules in the country, climatic conditions, and type of heating of the building. For example, in Europe, more than 60% of the consumed thermal insulation materials are glass wool, stone wool, and inorganic fibrous materials, while the use of polystyrene, organic foamy materials, expanded and extruded polystyrene constitutes less than 30% of the total [12].

It is recognized that the selection of materials is one of the most challenging and difficult steps of a building project [19]. At both the practical and scientific level, studies can be found in the literature focusing on finding the materials which are most suitable for a particular project. The Sustainable Development Goals have been pursued in different areas of economic activity; therefore, when choosing materials for the construction of buildings, not only are their physical and technical characteristics as well as economic factors taken into account, but also their social and environmental impacts [20]. A multi-criteria evaluation has become one of the most important tools in energy development studies in the last decade, allowing the comparison of different alternatives [21]. In this type of evaluation, the choice of methodology and its logical justification play a very important role. A correct choice of the evaluation method and the criteria on which the evaluation will be based can solve complex issues relating to the chosen alternatives.

This paper aims to give an in-depth view of existing multi-criteria decision-making (MCDM) applications for the selection of insulation materials and to provide major insights in order to simplify the process of method selection for future research. A systematic literature review is performed based on the Search, Appraisal, Synthesis and Analysis (SALSA) framework and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [22]. In order to determine which MCDM method is the most appropriate for different insulation problems, the main advantages and disadvantages of different methods are provided. In order to achieve this purpose, Section 2 provides the methodology. Section 3 presents an analysis of the selected articles for review: the techniques used in the studies in order to select criteria for evaluation and determining their weights are provided; the criteria used are overviewed and arranged around four dimensions. Section 4 focuses on the advantages and disadvantages of different MCDM methods.

2. Methodology

A systematic literature search and analysis was carried out in accordance with the SALSA framework. The methodology of SALSA allows one to minimize the possible factor of subjectivity and is indicated as one of the most suitable tools for identifying, evaluating, and systematizing literature [23], and guarantees the methodological precision and completeness [24]. The accuracy and completeness of the research are also ensured by the PRISMA statement [22]. The framework for the systematic literature search and review in this research is provided in Table 1.

Table 1. The framework for systematic literature search and review.

Stage	Description
Search	Key actions: keywords identification; search database. Research scope: MCDM methods for solving questions of sustainable insulation.
Appraisal	Key actions: papers selection through the PRISMA statement.
Synthesis	Key actions: data extraction and categorization.
Analysis	Key actions: analysis of the data, result comparison and conclusions.

Before starting the search through databases, it is important to define the scope of the research and to identify the appropriate keywords that will be used during the search process. The literature search was carried out in the Web of Science (WoS) database based on a combination of topics: "insulation" + "multi criteria". In order to carry out the widest analysis of the literature as possible and to include as many as possible research papers corresponding to the topic in the search, the search for papers was carried out in all WoS database categories.

The papers obtained during the search were evaluated and the PRISMA statement recommendations for selection of papers were followed. The inclusion criteria of the articles are as follows: keywords are in the title, the keywords section or the abstract of the paper, and the paper is published in a scientific peer-reviewed journal. Accordingly, exclusion criteria are as follows: review articles, conference proceedings; editorial letters; non English papers, and papers which were not primary research. These papers were excluded from the further analysis. Thus, 34 conference proceedings papers and 3 non-English papers were excluded from the content analysis. One hundred and nineteen articles were found by the search combination "insulation" and "multi criteria", 82 of which met the inclusion criteria. Articles that were included in the content analysis were mostly published in *Energy and Buildings* (10), *Building and Environment* (6) and *Sustainability* (5).

Content analysis was performed for the 82 articles found in the search. A snowballing method was also applied. Therefore, content analysis was performed for other articles that were not found during the search. Seven additional papers were found. A total of 18 relevant scientific studies were found where different MCDM methods for insulation materials were applied. A flow of information is provided in Figure 1.

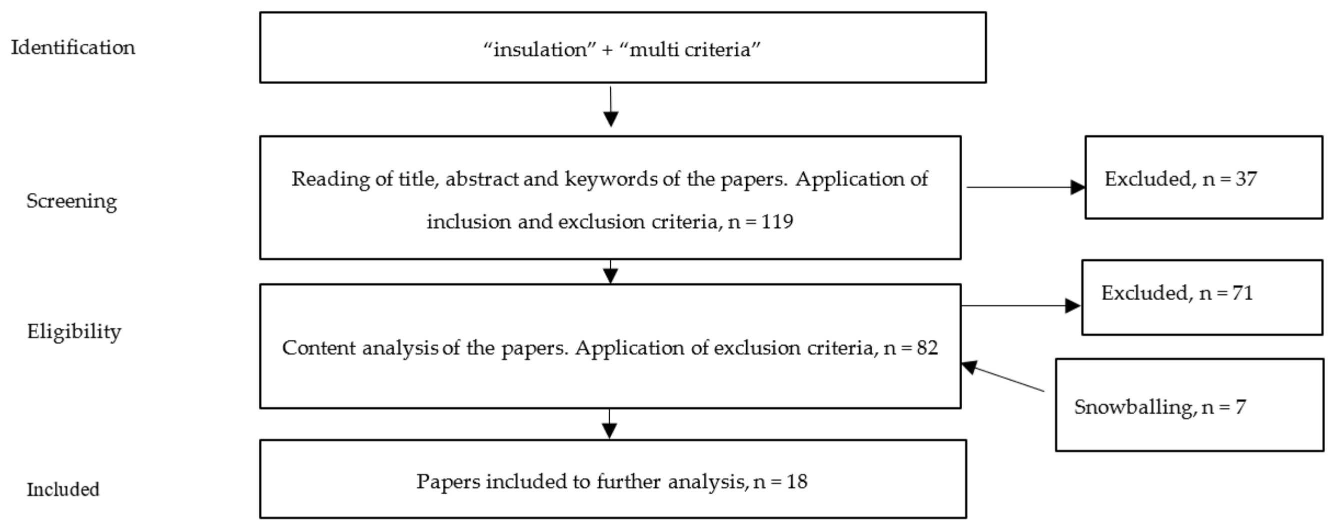

Figure 1. Flow of information (according to PRISMA).

The data of the selected articles were extracted and categorized according to the categories. Overall details of the reviewed studies are presented in Table 2. The next section provides detailed data on the analyzed articles.

Table 2. Overall data on the reviewed studies.

Application Areas	Methods Used	Groups of Indicators	Locations	Years of Publications
• Sustainability assessment • Guidelines for professionals • Suitability assessment	• The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) [25] • Analytical Hierarchy Process (AHP) [26] • Weighted Sum Method (WSM) [27] • VIKOR (an acronym in Serbian for multi-criteria optimization and compromise solution) [28] • Preference Ranking Organization Method for Enriching Evaluation V (PROMETHEE V) [29] • TODIM (an acronym in Portuguese for Interactive and Multi-criteria decision-making) [30] • Multi-Objective Optimisation by Ratio analysis (MOORA) [31,32] • Full Multiplicative Form of Multi-Objective Optimization by Ratio analysis (MULTIMOORA) [33] • Elimination and Choice Transcribing Reality (ELECTRE) [34,35] • Step-Wise Weight Assessment Ratio Analysis (SWARA) [36] • Simple Additive Weighting (SAW) [37] • Complex Proportional Assessment (COPRAS) [38]	• Economic • Social • Technological • Environmental • Performance • Energetic • Architectural • Not specified	• Vilnius, Lithuania • Montreal, Canada • Poznan, Poland • Turkey • Sarajevo, Serbia • Central Italy • Spain • Oran, Algeria • Riga, Latvia	• 2008 (2) • 2012 (1) • 2013 (1) • 2014 (3) • 2016 (1) • 2017 (1) • 2018 (2) • 2019 (2) • 2020 (5)

3. Literature Review

In order to carry out detailed literature analysis and systematically provide insights about the methods, evaluation criteria, and evaluation procedures used in practice, the publications discussed below are first categorized by application area. The following sub-section provides detailed analysis of the criteria and characteristics of the evaluation process (involvement of experts, motives for the selection of the criteria, methods for determining weights).

3.1. Assessment of Insulation Materials

According to the aim of the research, the papers could be grouped in three categories: sustainability assessment, suitability assessment and methods selection. Although sustainability assessment articles account only for 20% of all selected articles, the studies in this group are new, and this therefore shows the relevance of the topic. Sustainability assessment articles are summarized in Table 3.

Table 3. Sustainability assessment category.

Source	Aim of the Study	MCDM Method	Evaluation Level	Case Study Location	Materials Assessed	Main Contribution of the Study:
[39]	To evaluate the impact of sustainable insulations on the environment and their economic suitability.	ELECTRE TRI-rC	Local	A farmhouse in central Italy	Hard fiberboard, mineralized wood, polystyrene foam slab, cork slab, rock wool, glass wool, kenaf fibers, hemp fibers, expanded perlite, polyurethane, expanded vermiculite, cellulose	An original framework for the assessment is presented. The overall sustainability of insulating materials was evaluated, applying energy and comfort optimization, life cycle assessment (LCA) and life cycle costing (LCC) analysis for criteria selection and multi-criteria approach for ranking the alternatives. The most desirable materials are polystyrene foam slabs, kenaf fibers, hemp fibers, and cellulose.
[40]	To assess sustainability of flat roof types according of indicators aligned to the Sustainable Development Goals of the United Nations.	TOPSIS, AHP	National	Three weather scenarios in Spain (Mediterranean, Oceanic, Continental)	Four representative flat roof types (self-protected roof, gravel finishing roof, floating flooring roof and green roof).	The sustainability of four flat roof types was evaluated, based on indicators reflecting the Sustainable Development Goals of the United Nations. A green roof is the most sustainable alternative for all the scenarios evaluated.
[41]	To identify the factors that influence the selection of building roof system and to evaluate traditional and green roof systems.	AHP	Global	-	Traditional roof, green roof	The most significant criteria are related to performance criteria group. According to criteria outline by experts, a green roof is selected as a better option than a traditional roof.
[42]	To introduce a framework for the evaluation of sustainability of buildings insulation materials and to assess organic and inorganic building insulation materials in the context of sustainability.	interval TOPSIS	Global	-	Rock wool, expanded polystyrene, extruded polystyrene, kenaf, sheep wool, recycled cotton, recycled glass, recycled PET, recycled textile	A framework is presented and sustainable insulations are evaluated. Recycled glass and sheep wool are the best options for building insulation materials in the context of sustainability.

An original framework for the assessment of sustainability of insulating materials was presented by Rocchi et al. [39]. The case study of a farmhouse in central Italy considers the sustainability of twelve solutions for roof insulation according to seven criteria. The criteria for the assessment included combining energy and thermal comfort optimization with the environmental and economic LLA and LCC analysis. The ELECTRE TRI-rC method is used for ranking the selected organic and inorganic building insulation alternatives. The results show that the most favorable materials are polystyrene foam slabs, kenaf fibers, hemp fibers, and cellulose.

Guzman-Sanchez et al. [40] prepared a set of seventeen indicators for the assessment of the sustainability of different flat roof types, based on indicators reflecting the Sustainable Development Goals of the United Nations. The authors combined two MCDM techniques—the Analytical Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). In order to determine the relative importance of indicators, the AHP method was used for weighting. The TOPSIS technique was used for ranking the alternatives. The assessment was carried out under different weather scenarios. The results show that green roofs are the most sustainable choice for all the scenarios analyzed, by virtue of their insulation, possibility to recycle, life cycle cost, embodied energy, water purification and ecosystem-related aspects.

Rosasco and Perini [41] identified factors influencing the selection of building roof systems and applied the AHP technique to evaluate traditional and green roof systems. Experts identified the criteria and their weights for the assessment, and the most significant criteria are related to the performance criteria group. According to the criteria selected, evaluation demonstrates that a green roof is a better option than a traditional roof.

Streimikiene et al. [42] applied the interval TOPSIS method for sustainability evaluation and ranking of organic and inorganic building insulation materials. The authors carried out the sensitivity analysis by applying four different scenarios (equal, balanced, technological and environmental) with different weights for the selected criteria. The assessment shows that the best alternative according to the three scenarios (equal, balanced and technological) is recycled glass. According to the assessment, sheep wool is the best option in the environmental scenario.

Suitability assessment articles account for 40% of all selected articles and are summarized in Table 4.

Civic and Vucijak [43] applied the VIKOR technique for the evaluation of eight insulation materials. The authors selected seven criteria, which represent technical and environmental aspects. In this study, both the selection of criteria and their weighting are based on the selection of authors. The results show that the most preferred option is styrofoam, second place was taken by glass wool, and the third best is wood wool.

Zagorskas et al. [44] applied the TOPSIS Grey method for ranking five modern insulation materials (eco wool, flax/hemp fiber, thermo wool, aerogel, and a vacuum panel) for retrofitting historical buildings. Eco-wool was ranked as the best insulation solution. However, the results of the other alternatives are quite similar.

Ruzgys et al. [45] analyzed design solutions of modernized buildings in Lithuania. The authors ranked six external wall insulation alternatives for building modernization (polystyrene foam and thin plaster; mineral wool and fiber cement panels), applying the integrated SWARA-TODIM method. It was found that the best alternative for residential building modernization is a ventilated system with 130 mm thickness mineral wool insulation and fibrocement panels.

Table 4. Suitability assessment category.

Source	Aim of the Study	MCDM Method	Evaluation Level	Case Study Location	Materials Assessed	Main Contribution of the Study:
[43]	To emphasize the importance of energy management in buildings and to evaluate selected insulation materials on criteria selected.	VIKOR	National	Sarajevo, Serbia	Styrofoam, mineral wool (stone wool and glass wool), pluto panels, polyester, polyurethane, perlite, wood wool	The best alternative, according the criteria selected, is styrofoam, second place is taken by glass wool and third place is occupied by wood wool.
[44]	To rank five modern insulation materials for retrofitting historical buildings.	TOPSIS	National	Riga, Latvia	Eco wool, flax/hemp fiber, thermo wool, aerogel, vacuum panel	Eco-wool was ranked as the best insulation solution for retrofitting the historical buildings.
[45]	To analyze design solutions of modernized buildings.	TODIM	Project	Vilnius, Lithuania	Polystyrene foam and thin plaster, mineral wool and fiber cement panels	The best alternative for residential building modernization is a ventilated system with 130 mm thickness mineral wool insulation and fibrocement panels.
[46]	To assess double-skin façade systems reflecting the experience of experts who have applied them.	AHP	National	Turkey	The four types of double-skin façades (multistorey, corridor, shaft-box, box window)	The box window took first place, second place was taken by the corridor, the multi-storey double-skin façade was third, and the shaft-box took last place in the assessment.
[47]	To introduce and characterize new polymer-based composite materials.	AHP	-	-	Different formulations of rice husk and cork granules	New polymer-based composite materials were presented and characterized according to thermal conductivity and stability, vapour resistance, heat capacity, and acoustic characteristics.
[48]	To analyze building thermo-modernization solutions.	WSM	Local	Poznan, Poland	External polystyrene, mineral wool, extruded polystyrene	The best ranked solution is the variant of additional thermal insulation of extruded polystyrene with an additional thickness of 30 cm and wood windows.
[49]	To assess double-skin façade systems reflecting the experience of experts who have applied them and to compare the results with a previous study.	Fuzzy AHP	National	Turkey	The four types of double-skin façades (multistorey, corridor, shaft-box, box window)	The box window took first place, second place was taken by the corridor, the multi-storey double-skin façade was third, and the shaft-box took last place in the assessment.

Marques et al. [47] introduced innovative composite materials that incorporate rice husk and cork granules. The materials presented comprise a sustainable building solution. The AHP method was applied for different formulations with different ratios of materials. The results of the experiment show that a higher portion of rice husk in the composite formulations can provide better acoustic performance. Expanded cork granules reduce the thermal conductivity.

The four types of double-skin façade (multistorey, corridor, shaft-box, box window) were evaluated by Bostancioglu [49] The alternatives were ranked according to fuzzy AHP. The box window the first place, second place was taken by the corridor, the multi-storey double-skin façade was third, and the shaft-box took last place in the assessment.. It was found that a box window is the best alternative according to three criteria (noise and thermal insulation, fire protection). The results of the study were compared with previous research, where double-skin façades were evaluated with the AHP method [46]. The ranking of alternatives was unchanged.

Basinska et al. [48] analyzed building thermo-modernization solutions. The authors used the WSM method to find the best solution in regard to economic, energy-related, and environmental criteria. A total more than 400 possible solutions were analyzed. It was determined that the best solution is the variant of additional thermal insulation of extruded polystyrene with additional thickness of 30 cm and wood windows. The results show that the use of insulation with a thickness above 36 cm does not provide a significant energy or economic effect.

Methods selection articles account for 40% of all selected articles and are summarized in Table 5.

Table 5. Methods selection category.

Source	Aim of the Study	MCDM Method	Evaluation Level	Case Study Location	Materials Assessed	Main Contribution of the Study
[50]	To present an approach for the assessment of wall insulation alternatives and to find the best wall insulation solution.	SAW, TOPSIS, VIKOR, COPRAS	Project	Vilnius, Lithuania	Wall insulation (not specified)	The method for ranking alternatives was proposed and applied.
[51]	To present a methodology that allows one to rank different design solutions of a building's external walls, evaluating qualitative and quantitative attributes.	COPRAS, COPRAS-G (COPRAS with Grey relations)	-	-	Four external wall alternatives with insulation of rock wool or expanded polystyrene	The method for ranking alternatives was proposed and applied.
[52]	To find an optimal alternative for building renovation.	MOORA and MULTIMOORA	National	Vilnius, Lithuania	Walls, roofs, ceilings, windows (not specified)	The method for ranking alternatives was proposed and applied.
[53]	To present an approach for the assessment and ranking of technologies in the construction sector.	ELECTRE IV, MULTIMOORA, TOPSIS, ELECTRE III, VIKOR	National	Vilnius, Lithuania	Six alternatives (mineral wool, polystyrene foam)	The method for ranking alternatives was proposed and applied.
[54]	To introduce a tool for ranking different renovation solutions and exemplify it by evaluating a real-life case building.	PROMETHEE V	Local	Oran, Algeria	Exterior insulation of the facade or roof with expanded polystyrene, cellular concrete, wood fiber, lime hemp plaster; double glazing window; double windows; secondary glazing	The tool for ranking renovation solutions is presented and fifteen different insulation alternatives are evaluated. The results of the assessment show that the best solution is the exterior insulation of the roof with expanded polystyrene.
[55]	To create an assessment tool for the residential house construction materials selection.	MULTIMOORA-SVNS (Multiobjective Optimisation by Ratio Analysis Plus Full Multiplicative Form—Single-Valued Neutrosophic Set)	National	Lithuania	Houses with different thermal insulation alternatives (walls, roofs, ceilings, windows)	The method was proposed and applied.
[56]	To provide guidelines in achieving a high-performance facade system.	AHP	Local	Montreal, Canada	Four facade alternatives (combinations of 2 wall and 2 window systems)	The guidelines for each design phase are provided. An approach for decision making relating to the design of building facades is introduced.

Zavadskas et al. [51] presented a methodology that allows one to rank different design solutions of a building's external walls. The methodology involves qualitative and quantitative attributes and is based on the COPRAS technique. Ginevicius et al. [50] applied several MCDM methods (SAW, TOPSIS, VIKOR, COPRAS) for ranking five external wall insulation solutions and to select the most economically effective alternative for the renovation of a building. The study evaluates offers from subcontractors. Zavadskas et al. [53] presented an approach for the assessment and ranking of technologies in the construction sector. The authors evaluated six alternatives to mineral wool and polystyrene foam for thermal insulation of external walls. The assessment was based on ELECTRE IV, MULTIMOORA and hybrid SWARA-TOPSIS, SWARA-ELECTRE III and SWARA-VIKOR approaches. Another study by Zavadskas et al. [55] introduced a tool for the residential house construction materials selection based on MULTIMOORA and Neutrosophic sets. The proposed new extension of MULTIMOORA was named MULTIMOORA-SVNS. The study by Brauers et al. [52] evaluated twenty alternatives for external walls, roofs, ceilings, and windows in order to find the best alternative for the renovation of masonry buildings in Lithuania. The multi-criteria evaluation was carried out based on MOORA and MULTIMOORA.

Seddiki et al. [54] introduced a tool for ranking different renovation solutions. The tool is based on the MCDM PROMETHEE technique and combines Delphi method for criteria selection and Swing method for the determination of the weights of the criteria selected. A case study of a building in Algeria is provided and fifteen insulation alternatives are evaluated. It was determined that the best solution is the exterior insulation of the roof with expanded polystyrene.

Moghtadernejad et al. [56] presented an approach for the decision making of the design of a building façade. The approach integrated the MCDM tool AHP and Choquet integrals. The guidelines for each design phase are presented in the paper. The assessment also includes the assessment of building insulation materials as one of the components of the building façade. The criteria for evaluation are selected according to the objectives of the project and are not necessarily focused on the goals of sustainability.

3.2. Criteria for Assessment in MCDM Models

The majority of studies (67%) relied on experts (from 3 to 50) for evaluation. Most often, experts from the construction sector are involved. Some authors also relied on scientists and employees of state authorities who work in the field of construction or cultural heritage. Expert assistance can be used both in the selection of criteria and in determining the weights of the selected criteria. All studies that involved experts in the evaluation process used expert assistance in determining the weights of the criteria, but not all used experts to select the criteria. For the determination of the weight of criteria, an expert survey is usually used, in which the importance of the criteria is measured by pairwise comparison (scale 1–9, from 1 as "equally important" up to 9 as "extremely more important") (33% of studies), or by ranking from the most important to the least important (22% of studies). Some authors used their own estimation and expert surveys to determine weights [45,50], while others used Simon Roy Figueira's procedure [39], or the Swing method [54]. Evaluations which were made without the help of experts were based on the choice of the authors of the study by assigning weights to the criteria. In some studies (22%), experts participated in the selection of criteria [41,50,53,54]. Surveys, the Delphi method and cross-group discussion (brainstorming technique) were used for this purpose.

Articles in the methods selection category also use the concordance coefficient by Kendal calculation [50,51] and the determination of criteria weights by the SWARA method [45,53,55] to reasonably and logically determine criteria weights. The techniques used in the studies in order to select criteria for evaluation and to determine their weights are given in Table 6.

Table 6. Selection of criteria and determination of their weights in assessing insulation materials.

Source	MCDM Method	Supporting Methods	Way of Weighting	Experts	Type of Stakeholders	Number of Experts	Criteria Selection Process	Criteria
[50]	SAW, TOPSIS, VIKOR, COPRAS	Concordance coefficient by Kendal	Own estimation and expert survey (rating from the most important to the least important)	Yes	Experts in construction (from the Certification Centre of Construction Products, construction and reconstruction enterprises, researchers)	16	Experts survey	Not specified criteria
[51]	COPRAS, COPRAS-G	Concordance coefficient by Kendal	Experts survey (rating from the most important to the least important)	Yes	Experts (not specified)	39	Own selection	Not specified criteria
[52]	MOORA, MULTIMOORA	-	N/A	No	-	-	Own selection	Not specified criteria
[53]	ELECTRE IV, MULTIMOORA, TOPSIS, ELECTRE III, VIKOR	Determination of criteria weights by SWARA method	Experts survey (rating from the most important to the least important)	Yes	Experts in civil engineers and in heating, ventilation, and air conditioning	25	Experts (Delphi method)	Not specified criteria
[44]	TOPSIS	-	Experts (pairwise comparison)	Yes	Experts in the cultural heritage, climate change and energy sectors	5	Own selection	Not specified criteria
[45]	TODIM	Determination of criteria weights by SWARA method	Own estimation and expert survey (rating from the most important to the least important)	Yes	N/A	25	Own selection	Not specified criteria
[43]	VIKOR	-	Own estimation	No	-		Own selection	Not specified criteria
[54]	PROMETHEE V	Sensitivity analysis	Swing method	Yes	Experts in the building and energy sector	4	Experts (Delphi method)	Economic, energetic and architectural criteria
[55]	MULTIMOORA-SVNS	Determination of criteria weights by SWARA method; sensitivity analysis; Neutrosophic sets	Experts (pairwise comparison)	Yes	Experts in house design (architects, engineers, and designers)	10	Own selection	Not specified criteria

Table 6. *Cont.*

Source	MCDM Method	Supporting Methods	Way of Weighting	Experts	Type of Stakeholders	Number of Experts	Criteria Selection Process	Criteria
[39]	ELECTRE TRI-rC	Energy and comfort optimization, LCA, LCC analysis, sensitivity analysis	Experts (Simon Roy Figueira procedure)	Yes	Experts (not specified)	3	Derived from the hybrid method developed (LCC analysis and LCA)	Economic and environmental criteria
[40]	TOPSIS, AHP	Sensitivity analysis (different weighting scenarios)	Experts (Questionnaire)	Yes	Experts in the building sector	50	Literature—the United Nations Sustainable Development Goals	Not specified criteria
[41]	AHP	-	Experts (pairwise comparison)	Yes	Experts in the building sector (architects, engineers, and researchers)	30	Experts (cross-group discussion—brainstorming technique); Literature	Economic, social, environmental and performance criteria
[46]	AHP	-	Experts (pairwise comparison)	Yes	Experts in the building sector	21	Literature	Not specified criteria
[49]	Fuzzy AHP	-	Experts (pairwise comparison)	Yes	Experts in the building sector	21	Literature	Not specified criteria
[42]	interval TOPSIS	Sensitivity analysis (different weighting scenarios)	Own estimation (different weighting scenarios)	No	-	-	Own selection; Literature	Technological and Environmental criteria
[56]	AHP	The Choquet integral	Experts (pairwise comparison)	No	-	-	Own selection; Literature	Not specified criteria
[47]	AHP	Different weighting scenarios	Own estimation (different weighting scenarios)	No	-	-	Own selection	Not specified criteria
[48]	WSM	LCA, different weighting scenarios	The method presented by Mroz [57]	No	-	-	Own selection; Literature	Not specified criteria

It should be noted that the criteria selected for evaluation are not categorized in most studies (almost 80%). Only four researchers divided the criteria into groups representing different evaluation dimensions. Seddiki et al. [54] divided the criteria into economic, energetic and architectural criteria to assess different alternatives for the renovation of the facade of the building. Rocchi et al. [39] singled out economic and environmental criteria groups to evaluate the impact of sustainable insulations on the environment and economic suitability. Rosasco and Perini [41] identified economic, social, environmental and performance criteria to identify factors that have the greatest influence when choosing building roof systems. Streimikiene et al. [42], in assessing the sustainability of organic and inorganic building insulation materials, identified the groups of technological and environmental criteria.

As previously mentioned, sustainability issues became particularly relevant in the construction sector. Although authors did not divide the criteria into groups in their assessments, this can be done in order to determine the popularity of the applied criteria and representation for different sustainability dimensions. Table 7 provides information on the criteria used in the evaluations, which are divided into four categories representing the essence of sustainable development. The popularity of the applied criteria is also estimated.

Table 7. Overview of criteria (arranged around four dimensions).

Dimension	Criteria	Popularity, %	Source
Economic	Investment cost, price	72	[41,43–46,49–56]
	Energy losses, heat losses, energy consumption decrease, energy saving	28	[39,41,45,52,54]
	Payback period	17	[45,52,53]
	Maintenance and disposal cost, operations and maintenance costs, decommissioning costs;	11	[41,56]
	Annual energy consumption, primary energy index	11	[48,56]
	Total amount saved per year	6	[52]
	Life cycle cost	6	[40]
	Comfort performance	6	[39]
	Net present value	6	[39]
	Tax incentives	6	[41]
	Real estate benefit	6	[41]
	Global cost	6	[48]
Social	Aesthetic	39	[40,41,46,49,54–56]
	Health, respiratory inorganics	17	[39,41,42]
	Air quality and heat island reduction	6	[41]
Technological	Thermal transmittance, thermal resistance, thermal conductivity, heat transfer, thermal insulation, heat capacity, insulation properties	78	[40–44,46,47,49–53,55,56]
	Water absorption coefficient, water vapour diffusion, Moisture properties	44	[42–45,47,50,53,56]
	Duration of works, construction process, complexity of the installation	44	[44–46,49–51,53,56]
	Durability, risk of the fabric	33	[41,50,51,54–56]
	Fire protection, fire classification	33	[42,46,49,56]
	Acoustic noise reduction, noise control, noise insulation, sound transmission class	33	[40,41,46,47,49,56]
	Weight, dead load	33	[40,41,50,51,55,56]
	Loss of space, total thickness	11	[44,56]
	Density	11	[42,43]
	Specific heat	11	[42,43]
	Wind pressure resistance	11	[46,49]
	Daylight	11	[46,49]
	Adhesive joint strength	6	[50]
	Extraction force of a pin fixing thermal insulating board to solid materials	6	[50]
	Warranty period	6	[50]

Table 7. *Cont.*

Dimension	Criteria	Popularity, %	Source
	Wall load-bearing capacity	6	[55]
	Protection	6	[40]
Environmental	CO_2 emissions	22	[41–43,48]
	Environmental friendliness of materials, resource sustainability, recycled materials	22	[40,41,55,56]
	Solar power, window solar performance	11	[40,56]
	Biodiversity	11	[40,41]
	Non-renewable energy	6	[39]
	Ozone layer depletion	6	[39]
	Global warming	6	[39]
	Albedo coefficient	6	[40]
	Carbon sequestration	6	[40]
	Embodied carbon	6	[40]
	Embodied energy	6	[40]
	Runoff attenuation	6	[40]
	Water purification	6	[40]
	Reduction in runoff temperature	6	[40]
	Agricultural productivity	6	[40]

All studies used indicators of insulation materials reflecting technological aspects. Overall, 78% of studies included thermal insulation characteristics in the evaluation. The use of the water absorption coefficient (44%) and duration of works (44%) took second place in terms of popularity. In addition, one third of studies included durability (33%), fire classification (33%), noise insulation (33%) and weight (33%). Economic indicators were included in 89% of the studies. The economic dimension is most often reflected by the investment cost or price criteria used by different authors. Overall, 72% of studies included this criterion in the assessment of insulation materials. The second criterion in terms of popularity is energy losses or energy saving (28%), while the third is payback period (17%). The criteria for social dimension were evaluated in 45% of studies. The following two criteria were also used: aesthetic (39%) and health (17%). Indicators representing the environmental dimension were also included in 45% of studies. The most commonly applied indicators were CO_2 emissions (22%) and environmental friendliness of insulation materials (22%).

4. Comparison of MCDM Models

The literature review revealed twelve different MCDM methods that were used in order to choose the most suitable insulation materials for buildings based on different criteria. These methods have different characteristics and different possibilities to include data in the estimations. Table 8 provides pros and cons of the MCDM techniques that were used for assessment of insulation materials.

The most popular AHP technique, developed by Saaty [26], helps to solve multi-criteria tasks using a pairwise comparison scale. The calculation technique of this method is quite simple and calculation results are obtained relatively quickly compared to other methods; the method is easily applied in various fields (tasks of construction, energy and other sectors) [58], and is logical and based on a hierarchical structure, and therefore focuses on all selected criteria. However, it should be noted that experience data of decision-makers plays a very important role here to determine the weights of the criteria. This can complicate the evaluation process if there is more than one decision-maker. In addition, additional analysis is required to verify the results of the evaluation [59–62].

Table 8. Comparative evaluation of MCDM methods.

MCDM Models		**AHP**	**TOPSIS**	**MULTIMOORA**	**VIKOR**	**ELECTRE**	**COPRAS**	**MOORA**	**PROMETHEE**	**WSM**	**SWARA**	**SAW**	**TODIM**
Popularity for Selection of Insulation Materials in Buildings, %		**33**	**28**	**17**	**11**	**11**	**11**	**6**	**6**	**6**	**6**	**6**	**6**
Pros	Easy to calculate	x	x	x	x			x		x		x	
	Non-compensatory			x		x		x	x				
	Comprehensible logic of calculations		x	x	x			x					
	Robust to outliers				x				x				
Cons	For verification additional analysis is required	x				x				x		x	
	Requires subjective assumptions	x				x			x		x	x	

The TOPSIS method is the second most popular method used when choosing insulation materials. The technique presented by Hwang and Yoon [25] is based on measuring the distance to the ideal solution [63]. As seen in the previously discussed technique, the TOPSIS is distinguished for fairly simple calculations and quickly obtains evaluation results, and the logic of calculation is rational and understandable, expressed in a fairly simple mathematical form. Therefore, it is easy for the decision-maker to interpret the results obtained and to understand the significance of the evaluation criteria for the final result. However, the TOPSIS is based on the Euclidean distance; therefore, positive and negative values of criteria are not reflected in the calculations. It is important to mention the fact that a significant deviation from the ideal solution in one evaluation criterion has a significant impact on the final results of the evaluation [64,65], and therefore the method is not suitable for evaluation when the indicators differ significantly among themselves.

MOORA was presented by Brauers in 2004 [31] and is identified as an objective tool to select alternatives. This approach is based on the ratio system and the reference point techniques. The method uses desirable and undesirable criteria simultaneously for ranking. Due to its objectivity, comprehensible logic of calculations, and simplicity, the method is widely used and is more robust than other MCDM techniques. The full multiplicative form was added to the MOORA by Brauers and Zavadskas [33], and the new method was named MULTIMOORA. Consequently, MULTIMOORA consists of three approaches: the ratio system and the reference point techniques, and the full multiplicative form [66]. Like its basis, MOORA, the method developed on its basis is widely used to solve problems in different areas.

The multi-criteria assessment technique VIKOR was presented by Opricovic [28] in 1998; this method is widely used in various fields of decision making. In addition, it is popular to integrate VIKOR with other MCDM techniques [67]. The method is based on seeking to determine the positive and the negative ideal solution (closeness to the ideal). Unlike the TOPSIS method, the VIKOR technique takes into account the relative importance of the distances from the positive and the negative ideal solution [68]. It is recognized that the VIKOR technique is understandable and the computation process is quite simple, compared with other methods. Despite that, the results could be affected by the normalization procedure and weight strategy.

The ELECTRE method was introduced by Roy in 1968 [34]. ELECTRE requires the determination of the concordance and discordance indices, which involves lengthy computations. The method needs to be subjected to human intervention, because the decision maker has to select threshold values for the calculation of concordance and discordance indices [69]. It is also recognized that for verification of the results, additional analysis is required.

COPRAS was introduced by Zavadskas et al. in 1994 [38]. It is one of the compromise methods, because COPRAS determines the ratio to the best ideal solution and the ratio to the worst ideal solution. The MCDM technique uses a stepwise ranking and evaluation procedure in terms of significance and utility degree. In addition, it is worth mentioning that qualitative and quantitative information can be used in calculations.

The methods of the PROMETHEE group are recognized as one of the most accurate methods. Currently, several versions of it are being developed. The first version was created in 1986. It was proposed by Brans et al. [70]. Calculations allow the use of qualitative and quantitative information as well as the use of uncertain information. In addition, alternatives that are highly interchangeable can be compared [71–73]. It is recognized that it is an accurate and effective multi-criteria evaluation technique; however, it has complex mathematical expressions [62,74], requires specific abilities, and results are not obtained as quickly as, for example, in the case of the TOPSIS or AHP. In principle, the method is intended for professionals engaged in this type of calculation.

The WSM method introduced by Zadeh [27] became popular due to its simple form and easy calculation [75]. This method is quite primitive and is designed to solve single-dimensional issues [76,77]. The WSM can be used as a separate method or as a component of other methods [78]. However, the issue of insulation material does not cover a single dimension that should be evaluated; therefore, it is basically more suitable for use as a component of other methods.

The SWARA is a relatively new method introduced by Kersuliene et al. [36]. The method is based on the logical calculation of weights and relative importance of the criteria selected. The greatest attention in the calculations is focused on the involvement of experts and the justification for participation in determining the weights of the evaluation criteria [79]. It can be said that experts have a key role in decision making. Although the method is new, it is widely used when solving different multi-criteria tasks [74]. The method is useful for collecting and coordinating information from experts [80].

One of the oldest, simplest, most commonly used and widely known MCDM technique is SAW [37]. This method is based on the weighted average, where the overall score of an alternative is determined by the weighted sum of selected criteria values. The calculation algorithm is very easy and do not requires specific knowledge. One of the advantages of this method is the proportional linear transformation of the raw data. Despite this, the result of the assessment may not be logical, when the values of one or several criteria differ from others. Additional analysis is required for verification of the results.

The TODIM technique was presented by Gomes and Lima in 1991 [30] and is based on a pairwise comparison. Although the method was introduced 30 years ago, it is not very popular in solving multi-criteria problems. The extended technique has the possibility to incorporate uncertain information [81–83]. TODIM is also distinguished by a long and complex calculation process [84] and less experience in the field of decision-making.

Depending on the available data, the experience of the decision-maker, the accuracy of the desired result and of the possible cost of time, the highlighted characteristics of the MCDM methods provide alternatives that allow faster evaluation process in future research.

5. Conclusions

A content analysis of articles has revealed that one third of studies used the AHP method for evaluation. The AHP method is used in half of all evaluations in the categories of sustainability assessment and suitability assessment. Meanwhile, articles in the method selection category offer more diverse, complex methods, requiring specific knowledge and skills. The second most popular MCDM method is TOPSIS, which is applied in 28% of all studies. Both methods are quite simple and easy to apply in practice. They do not require complex calculations, high costs in terms of time, or specific knowledge of the person seeking the solution. Although articles of the method selection category offer more complex calculation algorithms, they are much more methodologically accurate and logical when there is a need to select criteria for evaluation and determining criteria weights.

The majority of studies relied on experts for evaluation. All studies that involved experts in the evaluation process used expert assistance in determining the weights of the criteria, but not all used experts in the criteria selection process. For the determination of the weight of criteria, an expert survey is usually used, in which the importance of the criteria is measured by pairwise comparison or by ranking from the most important to the least important. For criteria selection, surveys, the Delphi method, and cross-group discussion (brainstorming technique) were used. Involvement of experts in the evaluation process reduces the subjectivity of the research and allows one to look at the problem being solved from different perspectives. The use of experts is recommended not only for the determination of weights, but also for criteria selection. In order to justify the involvement of experts in the evaluation process, scientific methods both for calculating the coincidence of expert opinion and for conducting the survey of experts should be used.

It should be noted that the criteria selected for evaluation are not categorized in most studies. All studies used indicators of insulation materials reflecting technological aspects, where thermal insulation characteristics were the most popular criteria. The economic dimension was evaluated in 89% of studies and mostly was reflected by the investment cost or price. The criteria for social and environmental dimensions were evaluated in 45% of studies. In order to carry out a comprehensive assessment of insulation materials, criteria representing different dimensions of sustainability should be used. The review of the evaluation criteria and their grouping by representing different dimensions makes it easier to select criteria for this type of assessment and ensures conformity of the evaluation with the current sustainability issues, which include the achievement of economic goals, energy efficiency, technological characteristics, and the impact on the environment and human health.

The conducted study provides an important input in guiding future studies on decision making for sustainable selection of insulation materials in buildings, which is the major issue in the Renovation Wave Strategy, aiming to improve the energy performance of buildings and at least doubling the renovation rates in the next ten years. As this strategy seeks to enhance the quality of life for people living in and using the buildings, the sustainability of materials needs to be properly addressed.

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